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# MONSANTO/WASHINGTON UNIVERSITY
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## THE EFFECT OF TIME AND TEMPERATURE ON THE MECHANICAL BEHAVIOR OF EPOXY COMPOSITES PART I. TANGENT MODULUS AND STRESS RELAXATION

BY

A. E. MOEHLENPAH
O. ISHAI
A. T. DIBENEDETTO

PROGRAM MANAGER
ROLF BUCHDAHL



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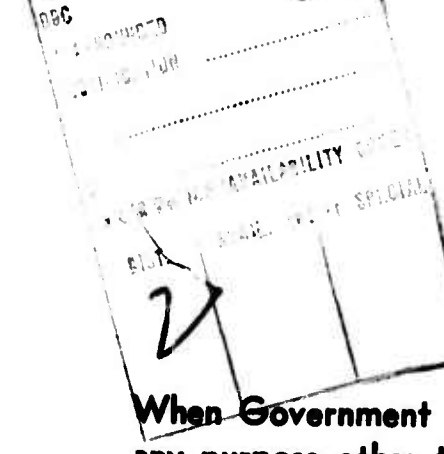


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A. E. Moehlenpah
O. Ishai
A. T. DiBenedetto

January 1970

Program Manager
Rolf Buchdahl



Monsanto Research Corporation
800 North Lindbergh Blvd.
St. Louis, Missouri 63166

## FOREWORD

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A. E. Moehlenpah*
O. Ishai**
A. T. DiBenedetto

Materials Research Laboratory
Washington University
St. Louis, Missouri 63130

## Abstract

A crosslinked epoxy resin consisting of a 60/40 weight ratio of Epon 815 and Versamid 140 and composites of this material with glass beads, unidirectional glass fibers and air (foams) were tested in compression and flexure to determine the effect of time and temperature on the tangent moduli and stress relaxation. Strain rates ranged from $10^{-4}$ to 10 $min^{-1}$ and the temperature ranged from -1 to 107°C.

Isotherms of tangent modulus versus strain rate were shifted to form master modulus curves. The modulus of a particulate filled composite or foam can be predicted from the modulus of the matrix over the entire strain rate range if one has knowledge of the reinforcement effect of the filler. The master curve for stress relaxation is of the same shape as the mirror image of the modulus master curve and can be used to estimate the modulus versus strain rate relationship if one value of modulus is known.

It was concluded that the time-temperature shift factors for tangent moduli and the time-temperature shift factors for stress relaxation were identical and were

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*Presently at Hydro-Air Engineering, Inc., St. Louis, Missouri.
**Presently in the Department of Mechanics at the Technion, Israel Institute of Technology, Haifa, Israel.

independent of the type and concentration of filler as well as the mode of loading. Thus the shift factors are a property of the matrix.

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Washington University
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## I. Introduction

The main object of this research was to determine the effect of temperature, strain rate and filler on the mechanical behavior of epoxy composites and to relate its short-term behavior to the long-term one.

Two types of tests were conducted; the first was to measure the stress as a function of strain at constant strain rate for different temperatures and filler contents and the second was stress relaxation at constant strain and temperature. These stress-time curves could be shifted along the time axis to give master stress relaxation curves.

In this paper the tangent moduli and stress relaxation will be discussed while a subsequent paper [1] will report on the mode of failure, yield stress and yield strain. Even though these composites are not elastic, the elastic theories yield useful guidelines for comparing matrix and composite modulus properties. Many theoretical [2-8] approaches are available for evaluating the moduli of elastic two-phase composite systems as a function of constituent material properties, the volume fraction of filler, the shape and degree of dispersion of the filler, and the degree of adhesion between the phases.

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*Presently at Hydro-Air Engineering, Inc., St. Louis, Missouri.
**Presently in the Department of Mechanics at the Technion, Israel Institute of Technology, Haifa, Israel.

Two theories that predict fairly well the effect of particulate filler on the elastic moduli will be given. Kerner [2] assumed spherical filler particles each surrounded by a shell of the matrix material which in turn is encapsulated in an intermediate zone. Assuming that $E_c/E_m = G_c/G_m$, his equation for a two-phase system reduces to,

$$\frac{E_c}{E_m} = \frac{15m\,C_f\,(1 - \nu_m) + (1 - C_f)\,[7 - 5\nu_m + m(8 - 10\nu_m)]}{15\,C_f\,(1 - \nu_m) + (1 - C_f)\,[7 - 5\nu_m + m(8 - 10\nu_m)]} \qquad (1)$$

where $E_c$ = elastic modulus of composite, $E_m$ = elastic modulus of unfilled matrix, m = ratio of modulus of filler to modulus of matrix (m = 0 for foams), $C_f$ = volume fraction of filler, and $\nu_m$ = Poisson's ratio of matrix.

Kenyon and Duffey [9], testing a glass bead filled epoxy in tension at room temperature and at a strain rate of 0.04 $min^{-1}$, found that Equation (1) fits their data well for volume fractions of filler up to 50 percent. They also found that modulus varied only slightly with the degree of adhesion between filler and matrix.

Whereas Kerner's equation was derived from a quite complicated mechanical analysis, Ishai's [8] approximate solution is based on a simple two-phase model of a cubic inclusion within a cubic matrix and assumes a uniform normal displacement at the boundary. The results can be formulated as follows:

$$\frac{E_c}{E_m} = 1 + \frac{C_f}{m/(m - 1) - C_f^{1/3}}. \qquad (2)$$

A drawback common to all approximate approaches is their failure to allow for the lateral effect, which is especially important at high rigid filler contents. However, Ishai and Cohen [10, 11], conducting compressive tests at room temperature, found that the effects of filler and voids on modulus can be predicted by Equation (2) up to volume

fractions of 50 percent. They used sand for particulate filler and air for voids with 50/50 Epon 815/Versamid 140 as the matrix.

Most experimental work reported in the literature has been done at room temperature, at one strain rate, and under just one mode of loading. The above elastic theories do not account for the change in modulus with strain rate. A few researchers have attempted to determine the effect of strain rate on the modulus of composites. Barnet and Cuevas [12], using both torsion pendulum and tensile tests, qualitatively state that for rigid epoxy resins the static tensile modulus is approximately equal to the dynamic modulus, while for flexible epoxy resins the dynamic modulus is greater. This observation is associated with the fact that the brittle resin was well below its glass transition temperature, $T_g$, while the ductile resin was near its $T_g$ at the test conditions. This shows that modulus is highly dependent on strain rate near $T_g$. Wells [13] reported flexural moduli in a more complex system of glass beads, fiber, and epoxy. Nicholas and Freudenthal [14] tested NaCl filled polyurethane in tension at high strain rates (.37 $sec^{-1}$ to 23.1 $sec^{-1}$) at room temperature. Their data show that the modulus of the composites increases with increase in strain rate and that the NaCl particles increase the composite to matrix modulus ratio more than spherical glass beads at corresponding volume fractions of filler.

Stress relaxation experiments are usually performed by applying a fixed deformation to a specimen and then measuring the load required to maintain that deformation as a function of time. "Stress relaxation measurements are generally made in a time interval somewhere between 1 and $10^6$ seconds. The upper limit is determined by the patience of the investigator. The lower limit is due to the fact that rapid stretching introduces

inertial and thermal effects" [15] and that the instruments recording the force and deformation have limited speed.

It is impractical to conduct tests for the long times necessary to confirm long-term behavior of plastics. The procedure which leads to the most reliable extrapolation of short-time data to very long times is that of time-temperature superposition [15-23]. Experimentally, the procedure is to select a reference temperature, $T_0$, at which engineering data are desired. For stress relaxation experiments modulus-time data at other temperatures, T, are shifted on the vertical axis by a factor $\rho T/\rho_0 T_0$, where $\rho$ is the density. The corrected data at different temperatures are then shifted along the log-time axis by a factor $A_T$, called a shift factor, until the best fit is observed. The shift factor is chosen as unity at the reference temperature $T_0$. If data are later desired at some other temperature, it is only necessary to shift the entire curve on the vertical axis by the factor $\rho T/\rho_0 T_0$ and on the horizontal axis by $A_T$ and a new master curve is obtained. For practical purposes the vertical shift factor, $\rho T/\rho_0 T_0$, is often omitted when it is known that no major density changes occur in the temperature interval covered as is the case for amorphous polymers.

While no completely convincing theoretical conception has yet been put forward to explain the validity of the time-temperature superposition principle for solid polymers, it has been verified by a number of investigators [24, 25]. In the temperature range from $T_g$ to $T_g$ + 100°C, the time-temperature dependence of stress relaxation of amorphous polymeric materials is usually correlated by the WLF [26] equation, where:

$$\log A_T = 17.4 (T - T_g) \Big/ [52 + (T - T_g)] \qquad (3)$$

In regions below $T_g$ the temperature dependence of the shift factor can usually be described by an exponential relation of the Arrhenius form [21, 22]:

$$\log A_T = \frac{Q}{\log e \, R}\left[\frac{1}{T} - \frac{1}{T_{ref}}\right] \tag{4}$$

where Q = apparent activation energy and R = universal gas constant.

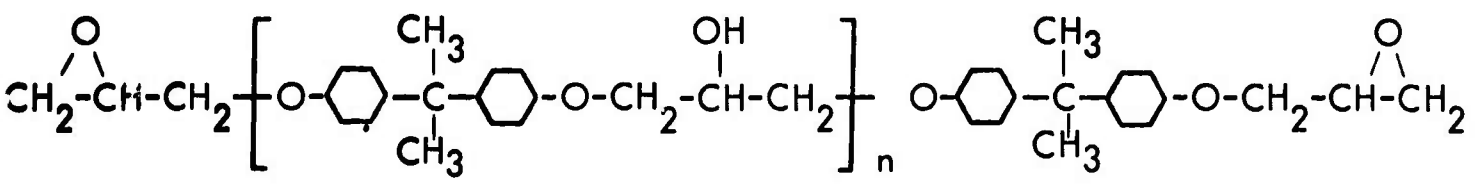
Time-temperature superposition demands that all relaxation times have the same temperature dependence, and this is a property of the amorphous phase. While non-interacting filler increases the magnitude of the modulus, previous investigations indicate that the shapes of the stress relaxation curves and magnitude of the shift factors are not changed by the addition of filler, although $T_g$ is changed slightly [27, 28]. Thus superposition principles are applicable to amorphous polymers containing non-interacting filler.

## II. Experiments

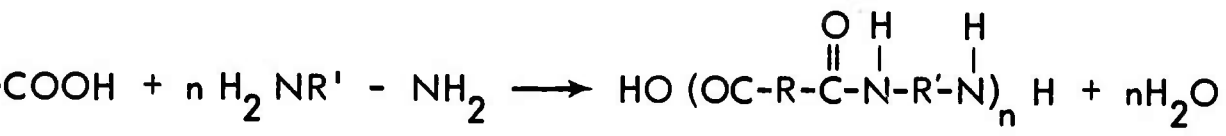
### A. Samples

#### 1. Constituent Materials

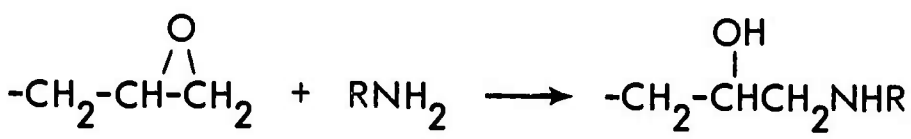
A 60/40 weight ratio of Shell Epon Resin 815 and General Mills Versamid 140 Polyamide Resin was chosen for the matrix material because of the low viscosity of the resins and the ductility of the hardened product. Epon resin 815 is a light-colored, low-viscosity, epichlorohydrin/bisphenol A-type epoxy resin containing a reactive diluent. The chemical structure of a typical molecule of the base resin is as follows:



Chemically the Versamid resins are condensation products of polyamines and diabasic acids.



Versamid 140 serves as both a curing agent and a plasticizer. The reaction with amines involves opening the epoxide ring to give a B-hydroxyamino linkage:



Since the Versamid amine has a functionality greater than 2, the final product between the Epon and Versamid is crosslinked. The final product is probably ductile because the R and R' in the amine and n in the epoxy can be large. The distance between crosslinks can be large, allowing flow to take place between the crosslink points. Also, the excess of Versamid serves to function as a plasticizer or blended copolymer.

Three types of filler were used with the Epon-Versamid matrix. The glass beads were supplied by the Flex-O-Lite Division of General Steel Industrial, Incorporated. The maximum particle size was 325 mesh. The density of the beads is approximately 2.3 g/cc and the Young's modulus is about $10 \times 10^6$ psi. The beads as supplied contained a substantial amount of steel dust. These particles were removed by stirring the beads with a teflon-coated magnetic stirrer. The metal dust adhered to the stirrer and was merely wiped off. This procedure was repeated until the stirrer no longer picked up any noticeable steel. Glass fibers obtained from Pittsburgh Plate Glass were used as the continuous filler. This E-glass roving (PPG 1062-Tf) was coated with an epoxy compatible coupler

supplied by the manufacturer. Approximate physical properties of the fibers are: density = 2.54 g/cc, tensile strength = $2 \times 10^5$ psi, Young's modulus = $10 \times 10^6$ psi, and Poisson's ratio = 0.22. Air was used as the foaming material.

2. Fabrication of Test Specimens

The following procedure was used to prepare the unfilled samples. The Versamid 140 and Epon 815 were heated separately to 40°C and evacuated in a vacuum oven. Then the components were mixed under vacuum and visually checked to see that the air was removed. Flexural and tensile samples were cast between two sheets of glass while the compressive samples were cast in test tubes. The resin was cured 24 hours at room temperature, 1/2 hour at 100°C, and 3-1/2 hours at 150°C.

The surface area to volume ratio of these molds is large, allowing for good heat transfer and preventing temperature gradients. Thus, the compressive samples are being cured under the same conditions as the tensile and flexural samples and will have the same molecular structure.

The glass molds were treated by release agent before casting the samples by applying a 20 percent by volume dimethyl dichlorosilane in carbon tetrachloride mixture to the surfaces of the glass sheets and test tubes. The molds were heated for five minutes in a 100°C oven and the coating procedure repeated three times. Rubber tubing was used for gasketing and two-inch by one-inch binder clips were used to hold the glass sheets and tubing together. Red garlock rubber gasketing material was used for spacing when 1/4-inch-thick sheets were cast. The resin was cured 24 hours at room temperature, 1/2 hour at 100°C, and 3-1/2 hours at 150°C.

Standard ASTM D-638 tensile samples were machined on a Tensilkut contour milling machine. The compressive cylinders were approximately 1/2 inch in diameter and were cut to lengths of approximately one inch with the use of a water-cooled diamond saw. The same saw was used to cut flexural bars which were approximately 1/4 x 1/4 x 3 inches. Exact sizes were measured with a micrometer.

The particulate filled samples were prepared in practically the same manner except that the glass beads were added to the Epon 815, stirred and evacuated before the versamid was added. Weight percentages of glass beads were about 37 percent. Approximately the same technique was used to prepare foam samples except that vacuum was not applied and air was whipped into the mixture. All foam samples tested were from one resin batch to obtain the highest uniformity of samples.

Continuous filled unidirectional specimens were cut from composite plates that were made on a filament winder specially designed by the Monsanto/Washington University Association. A square mandrel, 10 inches by 6 inches on each of the four faces, was used for the winding of the fibers. The fibers were E-glass roving (PPG 1062-T4) coated with an epoxy compatible coupler supplied by the manufacturer. Two percent by weight of dichloromethane was added to the 60/40 Epon-Versamid resin in order to minimize void formation. Because the boiling point of this substance is 40.2°C at atmospheric pressure, it is felt that this liquid completely volatizes during the subsequently described vacuum treatment and does not affect the properties of the resin. The glass roving was tensioned during winding by a two pound "trolley car" weight riding on the roving.

After winding the desired number of layers (50 for the plates that were intended for testing in the transverse orientation in compression and flexure and 12 layers for the other plates), the composite on the mandrel was then placed in a vacuum chamber at 1-2 mm mercury for five minutes. Release of the vacuum was followed by reapplication of vacuum for an additional 25 minutes. At the conclusion of the vacuum treatment, aluminum face plates were clamped to each of the mandrel faces and the desired thickness of the plate was obtained by fastening shims. The glass roving was then cut at two diagonally opposed corners to relieve the tension in the fibers. Finally, the composite while still on the mandrel was cured by circulating air at 100°C for 30 minutes and then at 150°C for 3-1/2 hours.

The continuous tensile and flexural specimens were cut to 1/4-inch widths from composite plates about 1/8-inch thick (12 wound layers). The tensile specimens were left as bars about six inches long, while the flexural samples were approximately three inches long. Specimens were cut at angles of 0, 20, 45, 60 and 90 degrees with respect to the fiber axis. All of the samples tested were cut from one set of four 6-inch by 10-inch plates. The compression samples were cut to approximately 1/2 x 1/2 x 1 inch sizes from a set of four 1/2-inch-thick (50 layers) plates.

## B. Equipment and Experimental Techniques

### 1. Density Determinations

Densities of the samples were used to check uniformity and to determine volume percents of filler. The samples were weighed on a Mettler balance and the volumes

calculated from sizes measured with micrometers. The density was determined to an accuracy of ± .5 percent.

2. Testing Procedure

Specimens were mounted on an Instron Testing Machine and loaded at constant rates of displacement. Cardboard spacers were taped to the Instron grips to properly align the tensile specimens. The Instron grips were initially spaced three inches apart for the tensile tests on continuous fiber-filled specimens and four inches apart for the other tensile tests. A rubber spacer that was taped to the lower platen was used to align the compression specimens. Spacers constructed of strips of masking tape were used to align the flexural specimens. All flexural specimens were tested at a two-inch gauge length with the exception of some transverse oriented continuous filled samples tested at four-inch gauge length. The load was constantly recorded on the chart and an electrical extensometer was used to measure the strain of the tensile samples. Since extensometers could not be used with flexural and compressive samples, the strain of the flexural and compression samples was determined from the recorder paper movement utilizing the paper to crosshead speed ratio and a calibrated correction of testing machine deflection versus load. The slope of the initial portion of the force versus deflection curve was used to determine the tangent modulus.

Stress relaxation experiments were done by moving the crosshead at a constant speed and then stopping it in the linear portion of the force-deformation curve. The relaxing force was then recorded as a function of time. To reduce the effect of humidity on the measurements, all samples were placed overnight in an oven at 85°C prior to

testing. The temperature was varied with the use of an Instron environmental chamber. The temperature was measured by a thermometer suspended with the bulb near the sample.

## III. Results

### 1. Tangent Moduli

The initial tangent modulus varies with both temperature and strain rate. Modulus increases with a decrease in temperature and with an increase in strain rate. Graphs of the log of the tangent modulus versus the log of strain rate at constant temperature were used to determine the modulus versus strain rate master curves. The compressive tangent modulus shift factors as a function of temperature are plotted in Figure 1 for unfilled, particulate filled, continuous transverse filled, and foam composites. The scatter of the modulus shift factors is primarily due to the relative difficulty of shifting curved lines, but it is clear that the shift factor is independent of filler type. The initial flexural tangent modulus shift factors versus temperature are shown in Figure 2 for the unfilled, particulate filled, continuous transverse filled, and foam materials. Neither the type nor geometry of the filler nor the mode of loading significantly affect the tangent modulus shift factors. The data shown in Figures 1 and 2 were curve fit by a least-squares-type technique to obtain Equation (5):

$$\log A_{T_E} = -0.1049 - .2071\,(T-50) - 1.243 \times 10^{-3}\,(T-50)^2 + 4.013 \times 10^{-5}\,(T-50)^3 \qquad (5)$$

This equation is indicated by the solid lines of Figures 1 and 2.

A visual summary of the modulus data is presented in the modulus master curves, Figures 3 and 4. The composites using particulate and continuous fiber filler have higher modulus than the unfilled matrix. Voids, in general, lower the modulus except in compression testing at the higher temperatures. The experimental compressive and flexural moduli of the foam and particulate-filled material are compared in Table I with the moduli calculated from the Kerner and Ishai equations. It can be seen from Table I and Figures 3 and 4 that these equations predict the modulus of the particulate-filled and foam composites fairly well at high values of shifted strain rate but deviate considerably especially in compression at low values of shifted strain rate where the material is more rubbery.

In comparing the experimental values of modulus in different modes of loading, it is seen that the values obtained in flexure are slightly lower than those obtained in compression. Experimentally, the flexural modulus is by far the easiest to obtain since one does not need extensometers or machine corrections for deflection. A major reason why the flexural modulus for composites is less than the compressive modulus is that there is really no filler at the surface where stress is a maximum in a flexural test. Perhaps another reason for this is that the strain rate in a flexure specimen varies from zero at the neutral axis to a maximum at the outer edge. In other words, the average value of strain rate is less than that computed by simple beam theory and for this reason the measured modulus is lower. Thus, flexural measurements are questionable in regions where the material properties are strongly strain rate and/or temperature dependent.

2. Stress Relaxation

The stress relaxation curves of the log of the relaxation modulus versus log of

time were shifted to form stress relaxation master curves at a reference temperature of 50°C. The compressive and flexural stress relaxation shift factors are plotted as a function of temperature in Figures 5 and 6 for unfilled, particulate filled, continuous transverse, and foam material. Again it can be seen that the type of filler does not affect the shift factors. Also it can be seen that the shift factors for stress relaxation are the same as those for modulus except for a change in sign. The solid lines in Figures 5 and 6 are from Equation (5) except that the sign has been changed. These shift factors were used to obtain the stress relaxation master curves for compression and flexure. The curves are plotted in Figures 7 and 8 for the unfilled, particulate filled, continuous transverse and foam material. It can be noted by comparing Figure 3 with 7 and Figure 4 with 8 that the stress relaxation master curves and the modulus master curves for the same mode of loading are practically mirror images of one another except for a shift of three decades along the time axis. Thus modulus versus strain rate$^{-1}$ is related to stress relaxation modulus versus time and is equivalent dimensionally. This is significant in that stress relaxation data can be used to estimate the modulus versus strain rate relationship if one value of modulus is known. In a like manner, modulus versus strain rate data could be used to estimate stress relaxation.

## IV. Conclusions

Tangent moduli and stress relaxation of epoxy composites can be correlated by a time-temperature superposition principle. The time-temperature shift factors for tangent moduli and for stress relaxation are identical and are independent of mode of loading and type of filler. Thus the shift factors are a property of the matrix. The stress relaxation

master curve for a material is practically the mirror image of the modulus master curve except for a shift of three decades along the time axis.

Acknowledgment

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## LIST OF FIGURES AND TABLES

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## TABLE I. EXPERIMENTAL AND THEORETICAL MODULAR RATIOS $E_c/E_m$

Modular Ratios for Foam, m = 0, $C_V$ = .241

Equation (2) Modular Ratio = 0.613
Equation (1) Modular Ratio = 0.632 for Poisson's Ratio = .37
Equation (1) Modular Ratio = 0.654 for Poisson's Ratio = .50

Modular Ratios for Particulate Filled Using Actual Values of m, $C_F$ = .214

| | | EXPERIMENTAL COMPRESSION RESULTS | | | THEORETICAL | | | EXPERIMENTAL FLEXURAL RESULTS | | |
|---|---|---|---|---|---|---|---|---|---|---|
| log $(\dot{\epsilon} A_T)$ | m | log $E_m$ | log $E_c$ | $E_c/E_m$ | Eq.(2) | Eq.(1) $\nu_m$=.37 | Eq.(1) $\nu_m$=.50 | log $E_m$ | log $E_c$ | $E_c/E_m$ |
| -10.0 | 5849. | 3.233 | 3.685 | 2.835 | 1.533 | 1.598 | 1.680 | | | |
| -9.0 | 6916. | 3.160 | 3.537 | 2.383 | 1.533 | 1.598 | 1.680 | | | |
| -8.0 | 5505. | 3.259 | 3.890 | 4.274 | 1.533 | 1.598 | 1.680 | | | |
| -7.0 | 2628. | 3.580 | 4.358 | 5.996 | 1.532 | 1.598 | 1.680 | | | |
| -6.0 | 958. | 4.018 | 4.767 | 5.608 | 1.532 | 1.597 | 1.678 | 4.264 | 4.194 | 0.851 |
| -5.0 | 359. | 4.445 | 5.065 | 4.171 | 1.529 | 1.594 | 1.675 | 4.625 | 4.711 | 1.219 |
| -4.0 | 167. | 4.777 | 5.262 | 3.056 | 1.525 | 1.588 | 1.668 | 4.902 | 5.084 | 1.521 |
| -3.0 | 101. | 4.997 | 5.391 | 2.474 | 1.520 | 1.582 | 1.660 | 5.108 | 5.338 | 1.701 |
| -2.0 | 73. | 5.137 | 5.479 | 2.202 | 1.515 | 1.576 | 1.652 | 5.254 | 5.498 | 1.753 |
| -1.0 | 57. | 5.244 | 5.547 | 2.009 | 1.510 | 1.570 | 1.644 | 5.353 | 5.586 | 1.712 |
| 0.0 | 44. | 5.352 | 5.600 | 1.769 | 1.504 | 1.562 | 1.634 | 5.416 | 5.629 | 1.632 |
| 1.0 | 35. | 5.454 | 5.638 | 1.525 | 1.497 | 1.553 | 1.623 | 5.456 | 5.650 | 1.560 |
| 2.0 | 31. | 5.514 | 5.659 | 1.399 | 1.492 | 1.547 | 1.615 | 5.485 | 5.672 | 1.539 |
| 3.0 | 31. | 5.515 | 5.670 | 1.427 | 1.491 | 1.547 | 1.614 | 5.514 | 5.722 | 1.612 |
| 4.0 | 26. | 5.579 | 5.674 | 1.245 | 1.485 | 1.539 | 1.605 | 5.556 | 5.822 | 1.844 |

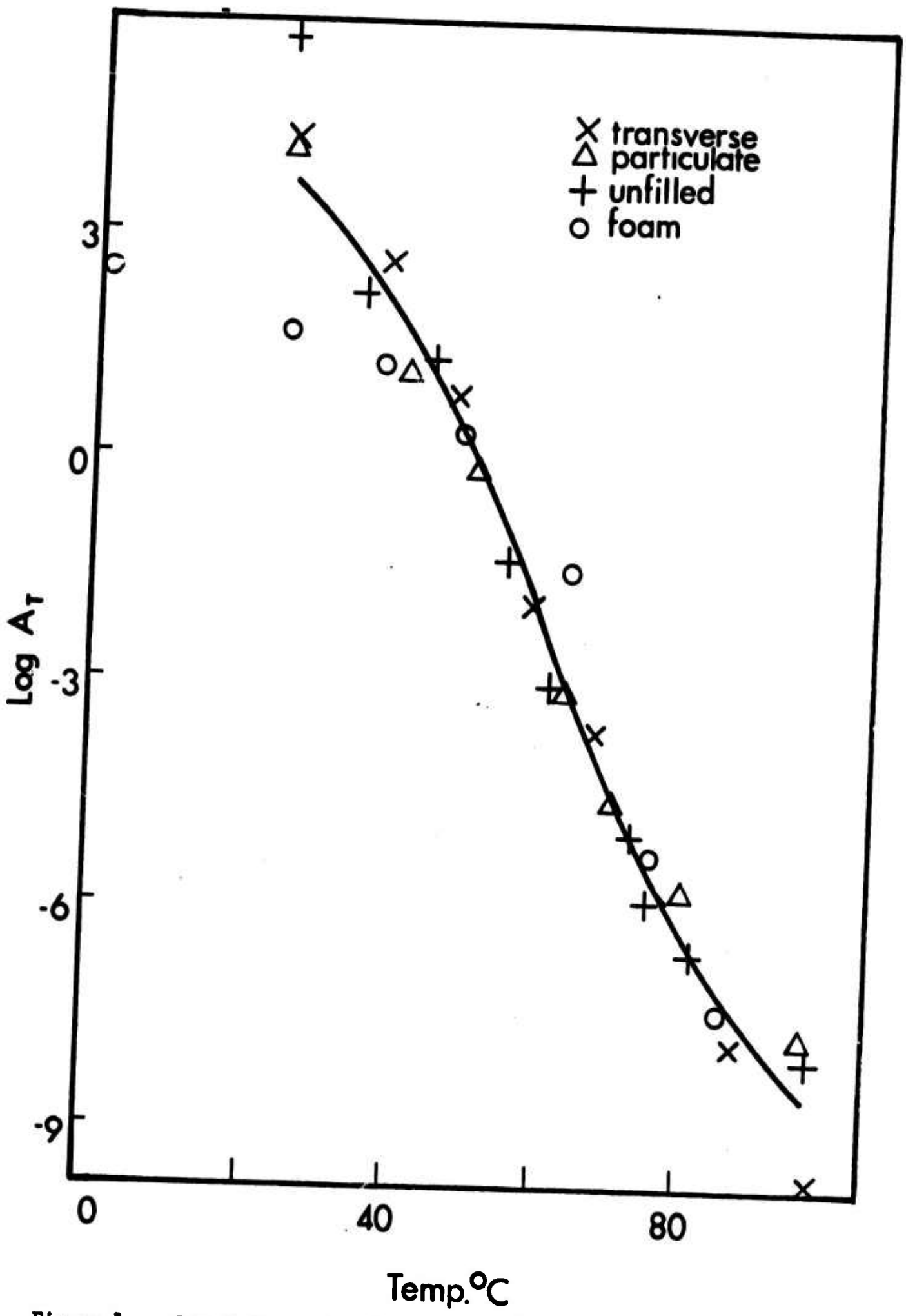


Figure 1 - Log Compressive Tangent Modulus Shift Factors versus Temperature for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

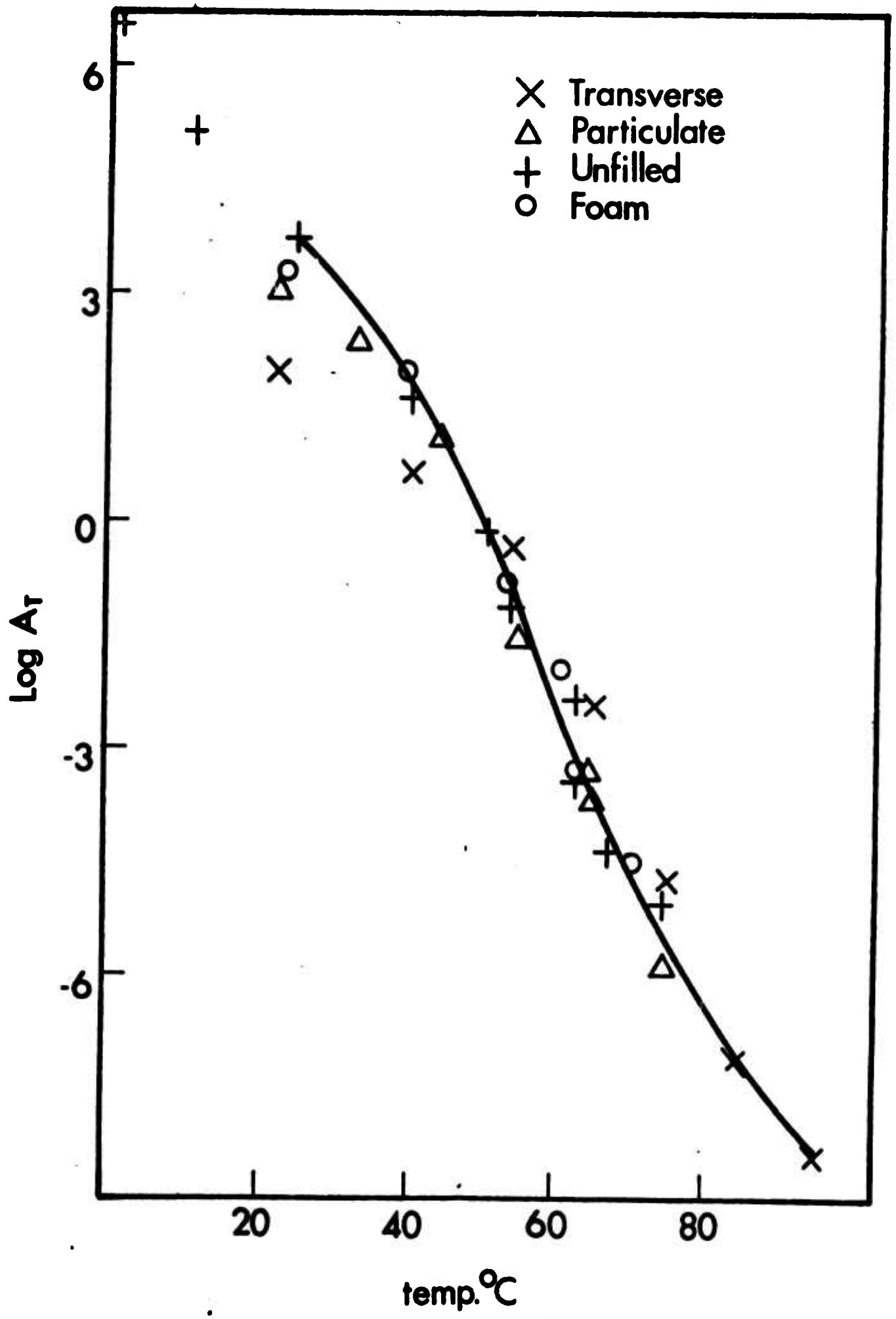


Figure 2 - Log Flexural Tangent Modulus Shift Factors versus Temperature for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

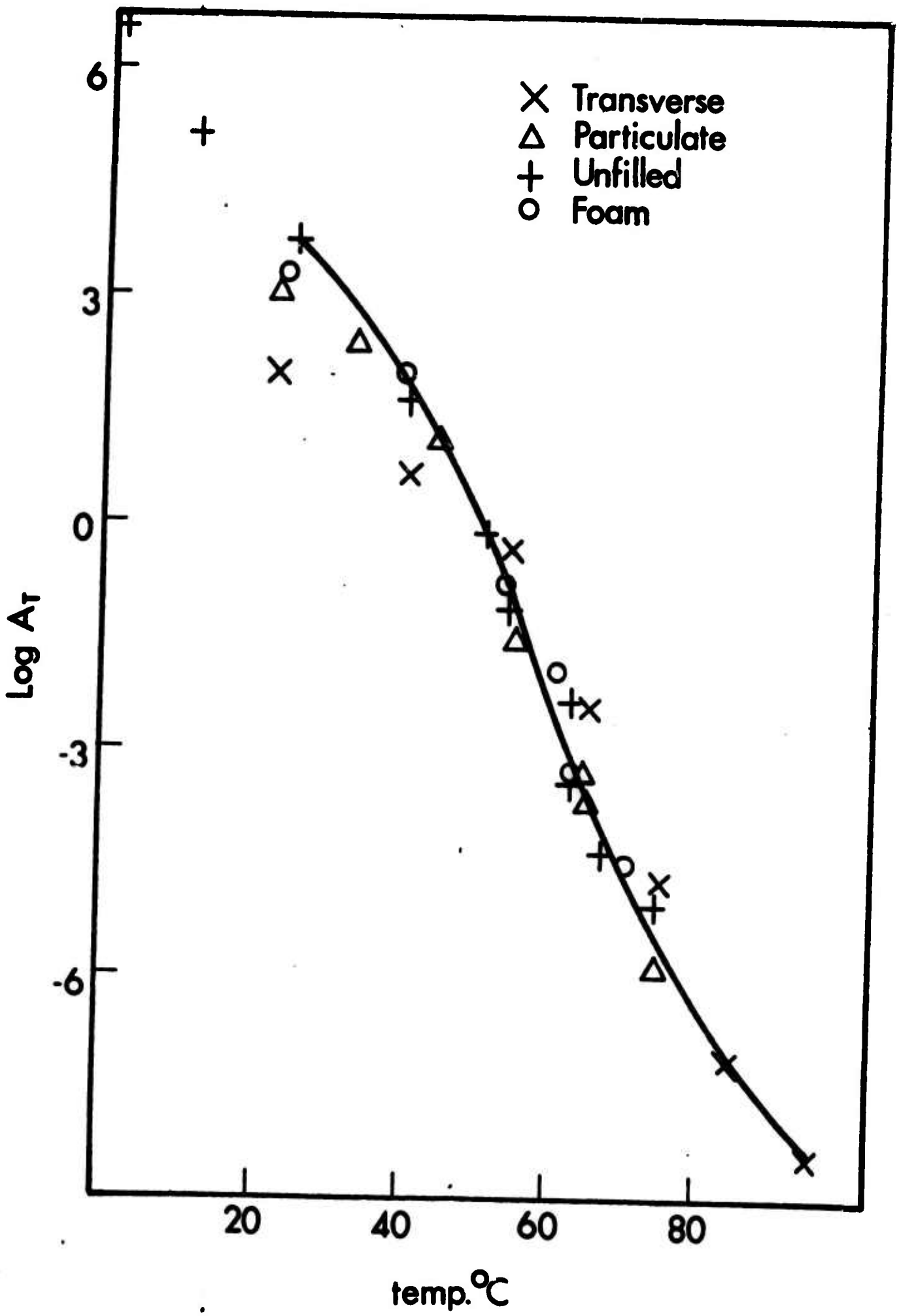


Figure 2 - Log Flexural Tangent Modulus Shift Factors versus Temperature for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

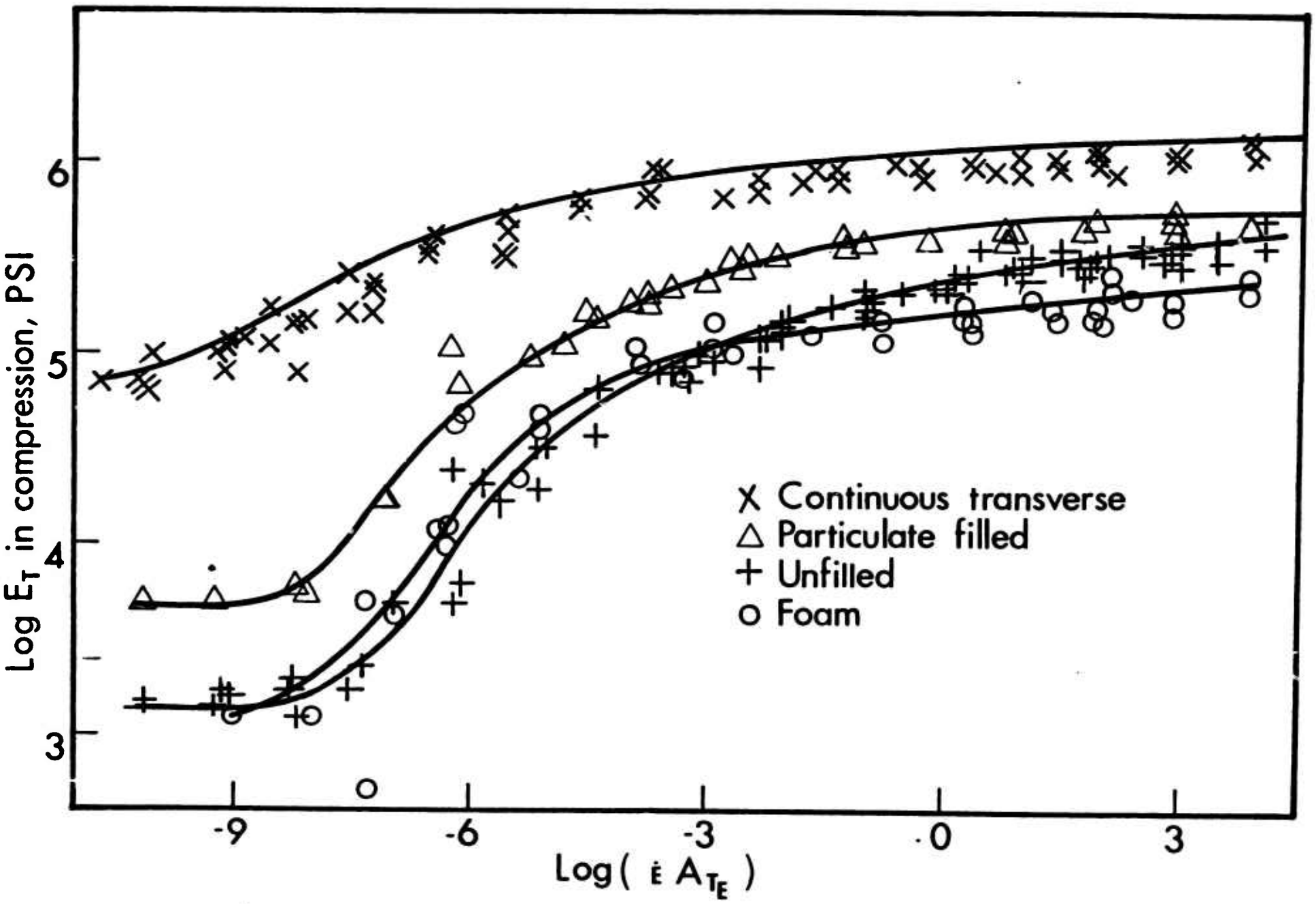


Figure 3 - Log Compressive Tangent Modulus versus Log Shifted Strain Rate for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

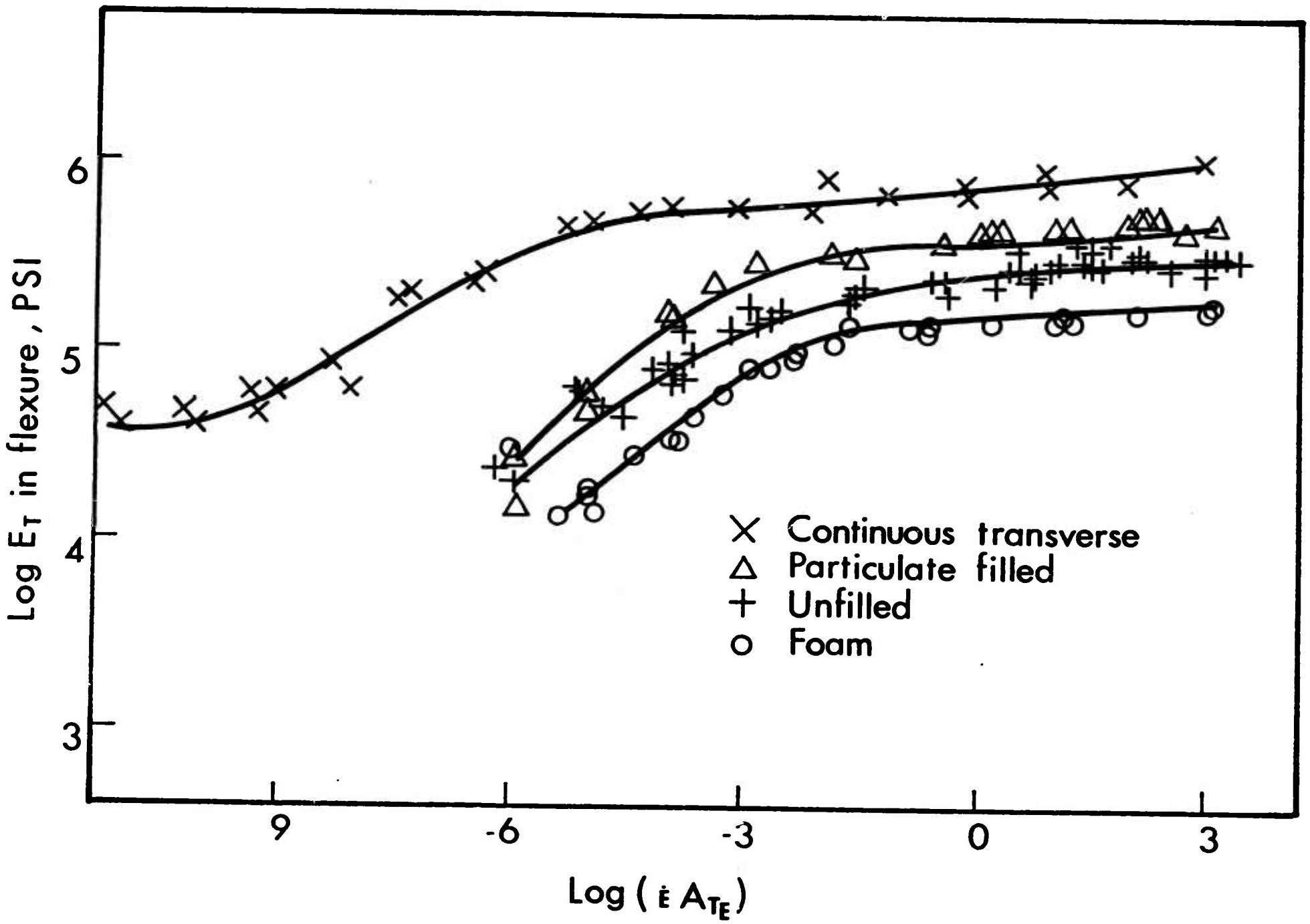


Figure 4 - Log Flexural Tangent Modulus versus Log Shifted Strain Rate for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

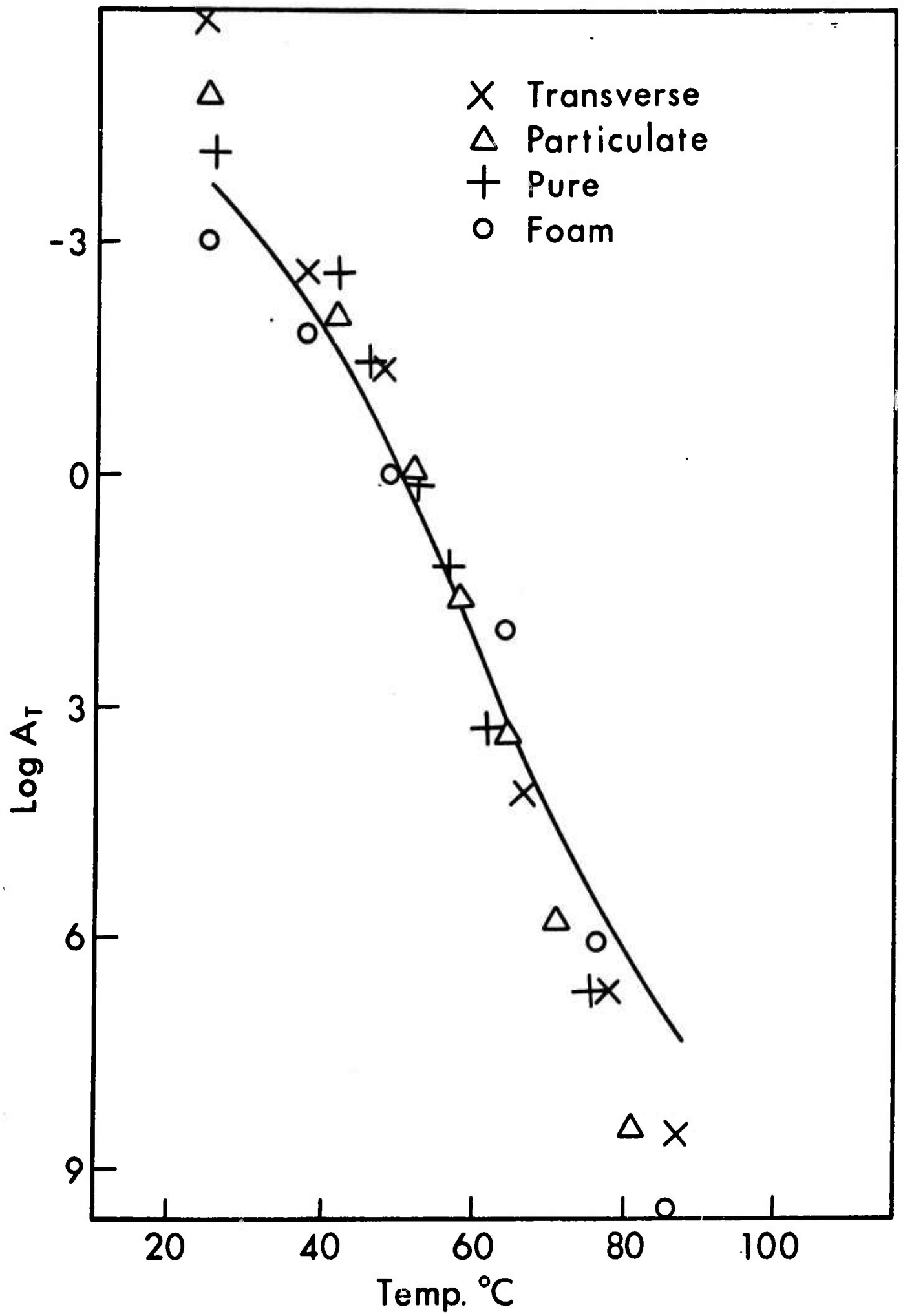


Figure 5 - Log Compressive Stress Relaxation Shift Factors versus Temperature for Unfilled, Particulate and Continuous Filled, and Foam, $T_{ref}$ = 50°C

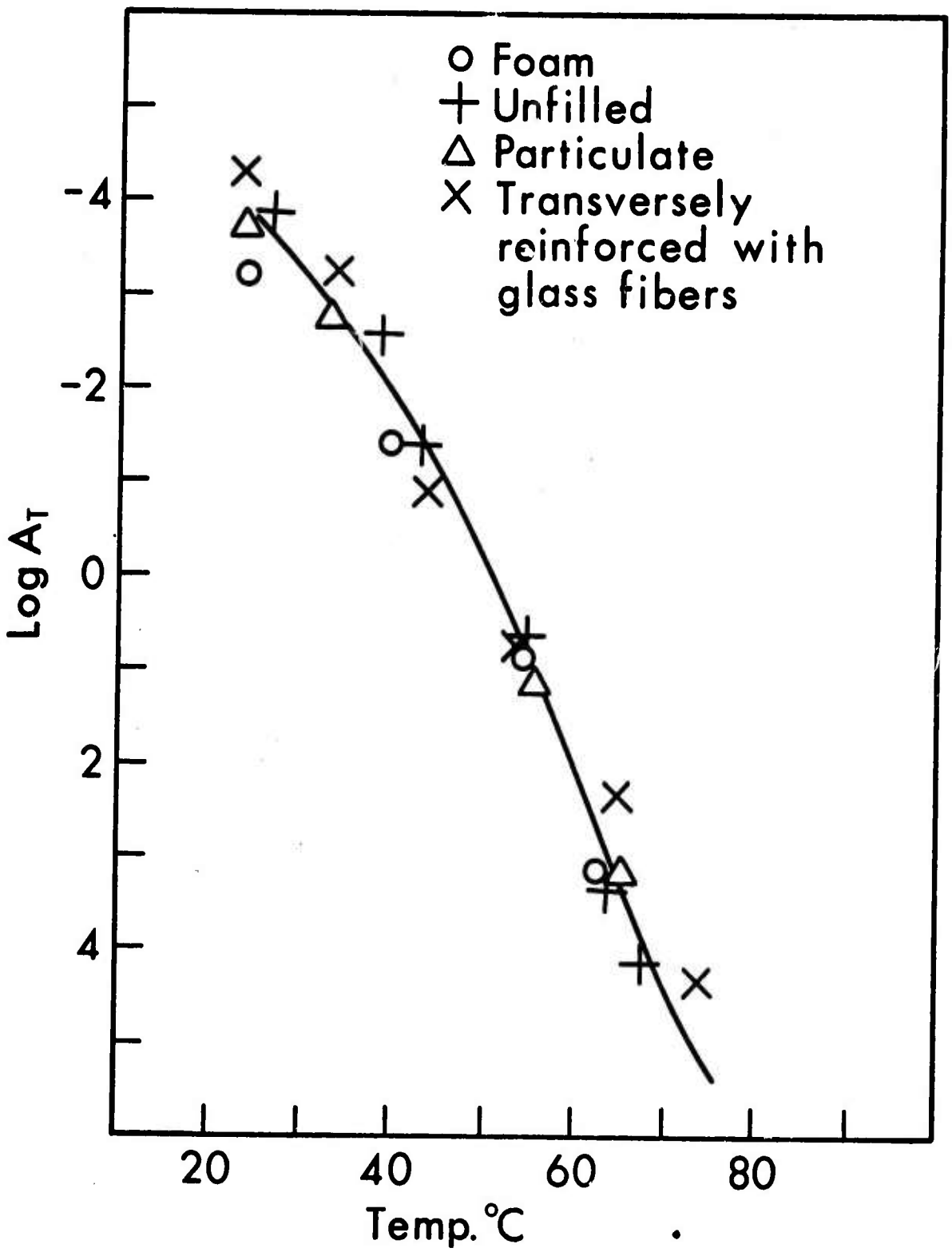


Figure 6 - Flexural Stress Relaxation Shift Factors for Filled and Unfilled Materials, $T_{ref} = 50°C$

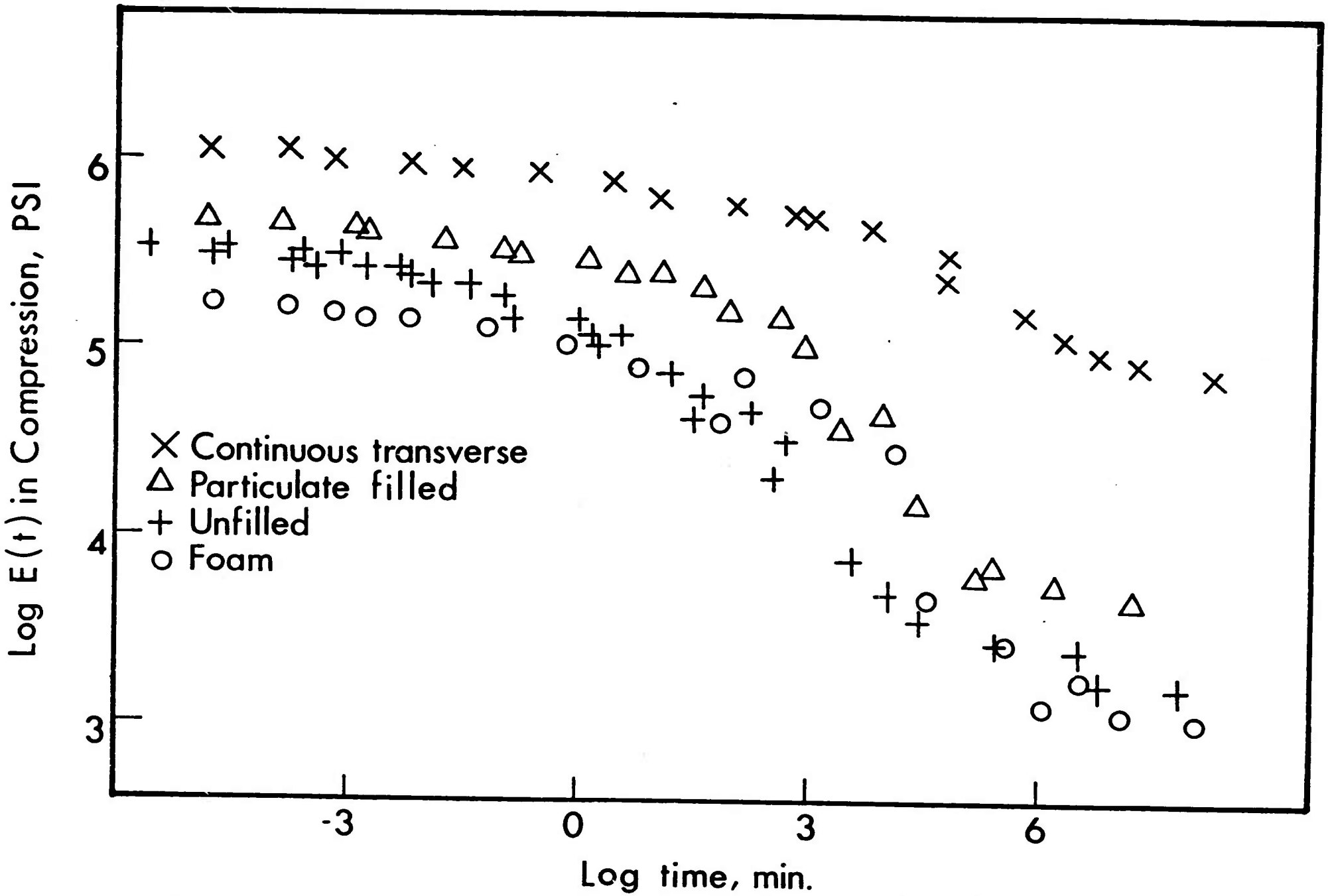


Figure 7 - Compression Stress Relaxation Master for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

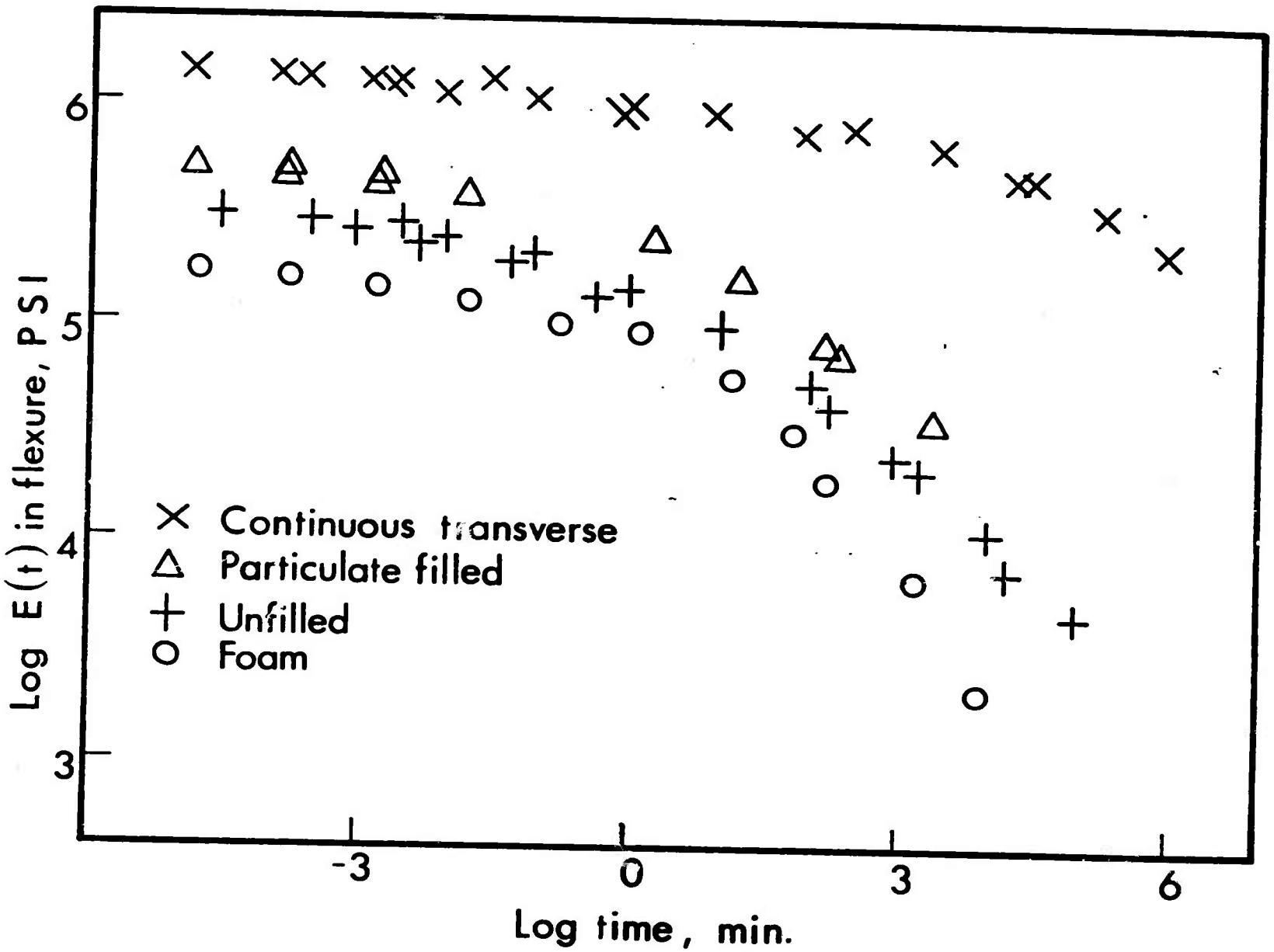


Figure 8 - Flexural Stress Relaxation Master for Unfilled, Particulate and Continuous Transverse Filled, and Foam, $T_{ref}$ = 50 °C

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13. ABSTRACT

A crosslinked epoxy resin consisting of a 60/40 weight ratio of Epon 815 and Versamid 140 and composites of this material with glass beads, unidirectional glass fibers and air (foams) were tested in compression and flexure to determine the effect of time and temperature on the tangent moduli and stress relaxation. Strain rates ranged from $10^{-4}$ to 10 $min^{-1}$ and the temperature ranged from -1 to 107°C.

Isotherms of tangent modulus versus strain rate were shifted to form master modulus curves. The modulus of a particulate filled composite or foam can be predicted from the modulus of the matrix over the entire strain rate range if one has knowledge of the reinforcement effect of the filler. The master curve for stress relaxation is of the same shape as the mirror image of the modulus master curve and can be used to estimate the modulus versus strain rate relationship if one value of modulus is known.

It was concluded that the time-temperature shift factors for tangent moduli and the time-temperature shift factors for stress relaxation were identical and were independent of the type and concentration of filler as well as the mode of loading. Thus the shift factors are a property of the matrix.

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| Yield stress | | | | | | |
| Stress-strain behavior | | | | | | |
| Stress relaxation | | | | | | |
| Time-temperature superposition | | | | | | |
| Epoxy resins | | | | | | |
| Epoxy composites | | | | | | |
| Shift factors | | | | | | |